TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ATTACHMENTS

SECTION 1.0
INTRODUCTION

The Atlantic Richfield Company (ARC) has prepared this Vadose Zone Modeling Report as Appendix I of the *Anaconda Evaporation Ponds Removal Action Characterization Data Summary Report* (RAC DSR). The RAC DSR was prepared pursuant to the *Anaconda Evaporation Ponds Removal Action Characterization Work Plan* (RAC Work Plan; Brown and Caldwell, 2008a) dated September 15, 2008 to assist in decision-making regarding removal actions associated with the inactive Anaconda evaporation ponds (Ponds). The removal action is: 1) required under the Administrative Order on Consent (AOC) and associated Scope of Work (SOW) [1] (2009 AOC/SOW), issued to the Atlantic Richfield Company (ARC) by the U.S. Environmental Protection Agency - Region 9 (EPA), dated April 21, 2009 (effective May 1, 2009); and 2) consistent with the Administrative Order for the Anaconda/Yerington Mine Site (Order; EPA Docket No. 9-2007-0005) issued by EPA to ARC on January 12, 2007. The Yerington Mine Site (Site) is located adjacent to the City of Yerington (Figure I-1-1).

Characterization activities conducted in the area of the Ponds consisted of: 1) a radiometric survey; 2) sampling and laboratory analysis of pond sediments, underlying alluvial soils and, where present, vat leach tailings (VLT) materials; and 3) groundwater grab sampling and laboratory analysis. As shown in Figure I-1-2, the Ponds are located in the northern portion of the Site, and consist of five Finger Evaporation Ponds (FEPs; the largest, FEP 5 is also known as the 'calcine tailings pond' or Thumb Pond), a Lined Evaporation Pond (LEP) and an Unlined Evaporation Pond (UEP). The Ponds comprise a portion of the Evaporation Ponds/Sulfide Tailings Operable Unit (OU-4), which also includes the sulfide tailings, the evaporation ponds associated with the pumpback wells, and the Weed Heights sewage lagoons (Figure I-1-2). The Ponds are located on private and public property, the latter managed by the U.S. Bureau of Land Management (BLM).

[1] Administrative Order on Consent and Settlement Agreement for Past Response Costs Anaconda Copper Mine, Yerington Nevada; U.S. EPA Region IX; CERCLA Docket No. 09-2009-0010.

1.1 Site Location and Physical Setting

The Site is located about one-half mile west and northwest of the City of Yerington in Lyon County, Nevada (Figure I-1-1), within the Mason Valley and the Walker River watershed. Agriculture is the principal economic activity in Mason Valley, typically hay and grain farming, onion production and some beef and dairy cattle ranches. The Walker River flows northerly and northeasterly between the Site and the City of Yerington (the river is within a quarter-mile of the southern portion of the Site). The Paiute Tribe Indian Reservation is located approximately 2.5 miles north of the Site (Figure I-1-1).

The physical setting of the Site is within the Basin-and-Range physiographic province, which is part of the Great Basin sagebrush-steppe ecosystem. Mason Valley occupies a structural graben (i.e., down-dropped faulted basin) typical of basin-and-range topography. The Singatse Range, located immediately south and west of the Site, is an uplifted mountain block that has been subjected to extensive hydrothermal alteration and metals mineralization in the geologic past. Mining and ore processing activities at the Site have resulted in modifications to the natural, pre-mining topography including a large open pit (occupied by a pit lake), waste rock and leached ore piles, and evaporation and tailings ponds.

The Site is located in a high desert environment characterized by an arid, strongly evaporative climate. Monthly average temperatures range from 33.3° F in December to 73.7° F in July. Annual average rainfall for the City of Yerington is approximately 5.3 inches per year, with lowest rainfall occurring between July and September (WRCC, 2007). The average annual pan evaporation at the Lahontan weather station, located approximately 30 miles north of the Site, is 68.8 inches (WRCC, 2007). Wind speed and direction at the Site are variable as a result of natural conditions and variable topographic features created by surface mining operations. Meteorological data collected since 2002 indicate that the dominant wind directions are to the north and the northeast (Brown and Caldwell, 2009).

1.2 Report Objectives

This Vadose Zone Modeling Report documents numerical modeling of the Pond sediments and unsaturated soils underlying the Ponds pursuant to the objective stated in the RAC Work Plan: 'Vadose zone characteristics of alluvial materials that underlie the ponds will be evaluated to determine the potential for current or future sourcing of chemicals to groundwater'. This Vadose Zone Modeling Report describes the approach, methods and results of numerical modeling to characterize the behavior of soil moisture in the unsaturated zone in response to atmospheric conditions, the physical characteristics of Pond solids and underlying soils, and depth to groundwater, as observed during the October 2008 field sampling program (this information, in part, is reproduced as Section 7.0 of the RAC DSR).

The resulting 'base-case' profiles for each of the Ponds, including two for the LEP, represented observed conditions to be simulated in the numerical models. In addition, model sensitivity simulations estimate the range of possible net soil moisture responses (i.e., potential wicking to the atmosphere or potential flux to groundwater, as soil moisture migrates vertically up and down within the soil column) resulting from variations in model input parameters (e.g., precipitation intensity, evaporation rate, osmotic suction results). Model sensitivity analyses for a select number of physical conditions also support the objective of assessing the potential for current or future sourcing of chemicals to groundwater.

A related objective of vadose zone modeling is to provide a quantitative basis for updating the conceptual model of the Ponds based on the interpretation of the 'base-case' and 'sensitivity' simulations (the conceptual model update presented in Section 9.0 of the RAC DSR also incorporates solids and groundwater geochemical data). Hydraulic conditions associated with the vadose zone underlying the Ponds will also be integrated into the data quality objectives (DQOs) to be presented in a future RI Work Plan for the Evaporation Ponds and Sulfide Tailings (OU-4). Specifically, results presented in this Vadose Zone Modeling Report can be used to identify specific areas of the Ponds for additional characterization activities (e.g., materials sampling and analysis, vadose zone monitoring).

SECTION 2.0
EVAPORATION POND SOLIDS AND SOILS CHARACTERIZATION

This Section describes the Pond solid materials and soils comprising the unsaturated zone underlying each of the Ponds, as presented in the RAC DSR. Per the RAC Work Plan, eight of the 17 borehole locations were sampled for geotechnical characterization (Figure I-2-1). Two subsurface samples from each borehole were submitted to Daniel B. Stephens & Associates, Inc. (DBS) for the following laboratory determinations: particle size analysis, saturated hydraulic conductivity, soil water retention characteristics, Atterberg limits and ASTM soil classification. An additional five samples of pond sediments collected by hand auguring were submitted to AMEC Earth & Environmental, Inc. (AMEC; Sparks, Nevada) for analyses of particle size and saturated hydraulic conductivity.

2.1 Pond and Soil Profiles

During drilling activities, soils were visually inspected and described by the field geologist and recorded in the field log books (RAC DSR, Appendix A). Field descriptions included general soil classification, color observations, and estimated soil moisture content. Detailed lithologic logs for each of the 17 boreholes drilled through the vadose zone to the shallow alluvial aquifer are provided in Appendix D of the RAC DSR. Based on field observations made during the drilling program, generalized solid material profiles for each of the Ponds were developed (Figure I-2-2), which are discussed below.

Lined Evaporation Pond – In terms of physical properties and observed hydraulic conditions, the LEP is represented by two end-member 'sub-areas': 1) areas of seasonal standing water ('wet' areas approximately outlined in Figure I-2-1); and 2) peripheral 'dry' areas. Transitional sediment and soil moisture conditions likely occur between the two 'sub-areas'. The differences between the 'wet' and 'dry' areas, as observed in the field, include Pond sediment characteristics (i.e., the presence of a surface crust of evaporite crystals) and the higher degree of saturation of Pond sediments and underlying VLT liner sub-base and alluvial soils in the 'wet' areas. The single profile for the LEP shown in Figure I-2-2 represents proximal 'wet' area Pond sediment and soil conditions based on laboratory results from sediment samples, and from the two characterization boreholes drilled in the LEP as described in Section 2.0 of the RAC DSR.

Throughout the LEP, a layer of yellow silty Pond sediments from three to 12 inches thick (six-inch average thickness), similar to the UEP sediments, was observed to be slightly to moderately moist in the 'dry' areas and completely saturated in the 'wet' areas. Given their proximity, Pond sediment and underlying soil hydraulic properties in the 'dry' southern portion of the LEP are anticipated to be similar to the characteristics of the sediments and soils associated with the UEP. Potentially, other peripheral 'dry' portions of the LEP may also be similar to the sediments and underlying soils associated with the UEP.

Within the LEP 'wet' areas, a cap (one- to three- inch thick) of soft white crystals overlain by a hardened 1-inch thick layer of crystals with a greenish color and a wrinkled texture was also observed (this surface crust could support the weight of an adult although the underlying material was fairly soft). The crystalline material is interpreted to be an evaporite salt, most likely a sulfate salt because of the high sulfate concentrations present in the spent process solutions although its chemical composition has not been determined. Pore water contained in these saturated Pond sediments was acidic (pH values commonly less than 1.0).

Underlying the LEP sediments is a thin asphalt liner situated on top of an eight- to 18-inch thick base of VLT. The asphalt liner is significantly degraded with cracking and crumbling of the material when exposed at the surface or where it underlies areas of thin Pond sediments. In areas where the liner has been protected by a thicker layer of sediments, the liner appears to be in fairly good condition. The VLT sub-base materials and shallow soils were observed to be saturated in the boreholes proximal to the 'wet' areas, indicating hydraulic communication between the saturated Pond sediments and the VLT/shallow alluvial soils.

Shallow soils under the LEP are generally characterized as silty materials with clays and sands which are associated with the distal alluvial fan depositional and transitional settings. Locally, within the 'wet' areas of the LEP, clays within the shallow soils were dense with a plastic characteristic. The occurrence of the dense clay material may result from: 1) natural conditions associated with the deposition of lake bed sediments in Pleistocene Lake Lahontan; 2) clay formation as a result of pre-mining agricultural practices in this area (Figure I-2-3); and/or 3) clay formation due to the leaching of shallow soils by the percolation of acidic solutions during Pond operations.

Unlined Evaporation Pond - The UEP consists of a top layer of yellow fine-grained pond sediment that is predominantly silt with up to about 12 percent clay and only minor sand. In the north-central and northwestern areas of the pond, a layer of red sediment up to 12 inches thick exists underneath the yellow sediment and probably represents the oldest pond sediments that accumulated at the start of mining operations prior to segregation of waste types into separate Pond areas. The measured thicknesses of pond sediments ranges from six to 72 inches, with the greatest thickness recorded in the small pond area at the southern tip (Figure I-2-1), and an average thickness of approximately 18 inches.

During sampling in October, the pond sediments were dry in the top three inches and increased to slightly moist below the surface but were never fully wet or saturated. The pond sediments are positioned directly on top of native soil with no liner material underneath. The contact with the soil was generally well defined but the top six inches of soil included ‘smeared’ pond sediments resulting from the retrieval of these materials from the plastic sleeve. Shallow soils were classified as predominantly silt with clay and sand, four- to 10 feet thick, and deeper soils consisted of interbedded layers of sand, silt and clay.

Finger Evaporation Pond 5 - FEP 5, also referred to as the Calcine Tailings Pond or Thumb Pond, has a different construction and operational history than the other FEPs. The sediments in this Pond are capped by VLT (six- to 18-inch cap), and consist of fine-grained red silts that vary in thickness from one inch to 11.5 feet (approximate average thickness of four feet). While the sediments at the time of sampling were observed to be slightly moist throughout most of the column, a two- to six-inch zone of very wet saturated sediment was observed just above the contact with native soils. The underlying alluvial soils were dry and were observed to be transitional in grain size between the soils underlying the FEPs, and the soils beneath the UEP and LEP.

Finger Evaporation Ponds 1-4 – The construction of FEPs 1 - 4 is similar to that of the LEP, with yellow silty Pond sediments overlying an asphalt lined (very limited or no VLT sub-base material was observed underneath the FEP liners). Pond sediments are only three to six inches thick, and were very dry at the time of sampling. Some areas of the FEPs also exhibited a hardened crust of evaporite salt crystals, although not as well developed as in the LEP (soft saturated sediments were not observed in the FEPs). The shallow alluvial soils under the liner are generally classified as silty sand with gravel (coarser grained than those soils under the LEP or UEP), which is consistent with their position on the distal edge of the alluvial fan.

2.2 Soil Geotechnical Analyses

Of the 136 Pond sediment and soil samples collected from the Ponds, 125 samples were pond sediments and shallow soils collected by hand augering that were submitted for geochemical and gravimetric moisture content analyses. Sixteen alluvial soil core samples were collected at shallow and deep intervals from the eight boreholes shown in in Figure I-2-1 for geotechnical testing at DBS (Albuquerque, New Mexico) to provide quantitative unsaturated hydraulic characteristics: grain size; in-situ moisture content; bulk density; saturated hydraulic conductivity (Ksat); Atterberg limits; soil suction versus moisture content relationships; and soil water characteristic curves. Tables I-2-1 and I-2-2 summarize the soil data. Soil water characteristic curves calculated by DBS and other laboratory data are provided as Attachment A.

Gravimetric moisture content (i.e., mass wetness) is defined as the mass of water in a soil divided by the mass of the soil. Determination of the gravimetric moisture content is done by weighing the soil sample as it is received, drying the soil in an oven at 105° Celsius, and then re-weighing the sample. Volumetric moisture content (i.e., volume wetness) is defined as the volume of water contained in a sample divided by the total volume of the sample. In clayey soils, the relative volume of water at saturation can exceed the porosity of the dry soil because clayey soils swell upon wetting (Hillel, 1980). Therefore, soils that are reported as being in excess of 100 percent saturation should be considered to be at 100 percent saturation. Gravimetric moisture content and volumetric moisture content are related according to the following equations:

$$\theta = \omega\rho b / \rho w$$
and
$$\omega = \theta\rho w / \rho b$$

where: θ = volumetric moisture content;

ω = gravimetric water content;

ρb = soil dry bulk density; and,

ρw = density of water.

The bulk density of water is approximately equal to one gram /cubic centimeter. Since the bulk density of soils is generally greater than that of water, the first equation above shows that volumetric moisture content is normally greater than gravimetric moisture content (Hillel, 1980). Degree of saturation is a measure of soil moisture that expresses the volume of water present in the soil with respect to the volume of the pores in the soil (Hillel, 1980). For soil with a porosity of 35 percent and a volumetric moisture content of 35 percent, the soil is considered to be 100 percent saturated.

Samples submitted for geochemical analysis were also analyzed for gravimetric moisture content, although the moisture content analysis was not the primary purpose for submittal. These samples were likely subjected to some degree of drying during storage and shipment, and therefore do not reflect in-situ conditions. These data are included as semi-quantitative indicators of moisture content. Volumetric moisture contents are not reported for these samples. These sample locations and the associated gravimetric water content determinations are presented in the RAC DSR.

Five additional Pond sediment samples (two samples from the UEP, two from the LEP, and one from the FEPs; Figure I-2-1) were collected by hand-coring and submitted to AMEC for grain size analysis and measurements of bulk density and Ksat. Moisture content, bulk density and Ksat results for these samples are presented in Table I-2-1 and laboratory data are provided in Attachment A.

Soil hydraulic properties were observed to vary over small vertical distances in the sample cores. For example, sample OU4-LEP-03A-SG is a silty sand (ASTM classification) based on grain size analysis (Table I-2-2), but the Ksat value for this sample (Table I-2-1) was measured at a value of less than or equal to 8.5E-10 centimeters per second (cm/s). A soil with the grain-size characteristics of a silty sand would typically exhibit a Ksat on the order of 1E-05 cm/s to 1E-03 cm/s (Domenico and Schwartz, 1990), or approximately five to seven orders of magnitude greater. Sample OU4-FEP-15A-SG was also identified by grain size analysis as a silty sand, with a measured Ksat value was 7.1E-05 cm/s. These examples of apparent discrepancies in hydraulic properties result from the use of discrete, relatively short core sections for Ksat measurements and an adjacent section of the same two- foot core for grain size analysis. Although these two samples are from within the same core, it appears likely that two material types are represented. Duplicate analyses were not performed to confirm this. This small-scale variability is accounted for in the development of the soil profiles for vadose zone modeling, and is an important aspect of the conceptual model for the Pond areas.

SECTION 3.0
VADOSE ZONE MODEL DEVELOPMENT

Development of the one-dimensional numerical unsaturated flow models of Pond profiles incorporated the field and laboratory data described in the previous section and in the RAC DSR, and the physical conditions at the Site (i.e., climate and depth-to-groundwater) that influence unsaturated flow of soil moisture. Columns (Pond profiles) were constructed for the LEP ('dry'), LEP ('wet'), UEP, FEP-5 and FEP 1– 4 to represent these data and conditions. As noted above, the LEP 'wet' and 'dry' columns were based on the data from the two characterization boreholes that were located adjacent to the area of ponded meteoric water (Figure I-2-1).

3.1 Modeling Code

The variably-saturated groundwater modeling code SVFlux™ (SoilVision Systems, 2008) was used to characterize the flux of meteoric water in the unsaturated zone underlying the Ponds. SVFlux™ provides a graphical modeling interface that allows the input of the various parameters that control the flux of water in the unsaturated zone, including the model domain geometry, location of the water table, material properties (i.e., soil types), and climate elements. SVFlux™ processes the model input data and writes a script file for the linked software FlexPDE™, which solves the partial differential equations governing unsaturated flow.

3.2 Atmospheric Input Data

Atmospheric input data for the model simulations included precipitation, potential evaporation, monthly average relative humidity and temperature obtained through the Western Regional Climate Center web site (http://www.wrcc.dri.edu/). Daily precipitation data used in the model simulations were obtained for the Yerington, Nevada Coop site #269229. A representative 15-year climate record was used for the simulations, from June 1972 through May 1987 (the simulation years are not coincident with a water year or calendar year, but are more likely to reflect the precipitation received in the water year rather than the calendar year, given the limited precipitation during the summer months). Table I-3-1 summarizes the 15-year climate record period used for the simulations. This period includes: 1) the range of average annual precipitation rates expected at the Site, represented by a greater number of below average (‘dry’) years (late 1970s to early 1980s) followed by a shorter number of above average (‘wet’) years (early to mid-1980s); and 2) a high precipitation year (8.99 inches in simulation year 11) that was 75 percent greater than the 5.12-inch annual average for the 95-year period of record (1914 through 2008) at Site # 269229. The selected climate period is intended to represent a range of typical precipitation years for the Site. A different distribution of dry and wet years would likely produce a correspondingly different annual distribution of meteoric water flux in the models, but is not anticipated to significantly change the long-term character of the results. For example, had the ‘wet’ years been included in the earlier years of the simulation period, potential fluxes of meteoric water to the groundwater would be expected to be greater in those early years, with lower potential flux to groundwater in the later portion of the simulation period.

Precipitation may be applied in a variety of ways to a numerical model. From a numerical standpoint, storm events are problematic if they start or end instantaneously. In order to smooth the numerical model calculations, storm events are scaled in smoothly on any particular day using either a parabolic or tetrahedral shape. These storm event shapes allow for a realistic application of storm events which minimizes possible issues in the numerical model. The SVFlux software performs calculations such that the total volume of water applied to the soil on any particular day is consistent with input data regardless of the storm shape selected. For the simulations presented here, the modeled temporal distribution of precipitation intensity was globally set to a parabolic distribution over an eight-hour period.

Evaporation data used in the model simulations are based on pan evaporation data obtained for the Lahontan, Nevada Coop site #264349, located approximately 30 miles north of the Site (evaporation data are not available for the Yerington, Nevada Coop site). Pan evaporation data from the Site were not used for modeling purposes because the Site data represents a period of less than 10 years, whereas the Lahontan site includes approximately 60 years of data. The Lahontan site was selected based on its proximity to the Site and the climatic similarity to the Site. Pan evaporation data are available as monthly average values for the period of record at the Lahontan site. Table I-3-2 presents these evaporation data as daily average evaporation rate by month.

Evaporation data used in the simulations were adjusted by a pan coefficient of 0.7 to correct for factors (e.g., storage and transfer of heat to the water from the sides of the evaporation pan), which may increase the evaporation rate in an open pan with respect to the potential evaporation from a crop or bare soil (coefficients vary from 0.35 to 0.85 for agricultural situations; UNFAO, 1998). The pan coefficient effect lowers the potential evaporative flux indicated by the pan evaporation data. The pan evaporation data were converted to metric units for consistency with other model inputs. Evaporation in the simulations was set to zero for days when precipitation occurred. Sensitivity of the models to changes in the pan factor is discussed under Section 5.0.

3.3 Material Properties

The physical properties of the Pond materials and underlying soils, and the climate conditions at the Site, control the upward or downward movement of soil water in the unsaturated zone. Pond sediment and soil profiles (Figure I-2-2) were developed to represent the general distribution of material types observed during the October 2008 field characterization program. Geotechnical laboratory data used to quantitatively characterize the saturated and unsaturated hydraulic properties of the Pond sediments and underlying alluvial soils were incorporated into the numerical models.

One of the primary quantitative soil characterizations is the relationship between soil moisture and soil pressure head, which is typically represented by a semi-log plot called a soil-water characteristic curve (SWCC). The SWCCs are fit to laboratory measurements of soil moisture content at varying negative pressure conditions using mathematical fitting algorithms. The method of Fredlund and Xing (1993) was used to fit the SWCCs for each of the materials using the soil properties database program SoilVision™ (SoilVision Systems, 2004). SWCCs were not developed in the lab for Pond sediments, and were estimated based on grain size distributions and bulk density determinations using the method of Wilson, et al. (1997) and SoilVision™. SWCCs for each of the materials incorporated into the numerical models are included in Attachment B.

After the SWCCs were established for the Pond sediments and underlying soils, the relationship between soil moisture content and unsaturated hydraulic conductivity was estimated with either the method of Fredlund, et al (1994), or the modified Campbell (SoilVision®, 2004) method, using the SoilVision™ software. Unlike saturated hydraulic conductivity, which is expressed as a single specific value that remains constant, unsaturated hydraulic conductivity decreases exponentially as soil moisture decreases. The method of Fredlund, et al (1994) was initially used to estimate this relationship for all of the materials, but the sharp discontinuity of the estimated hydraulic conductivity curve at residual suction was found to create numerical instabilities in the simulations for some of the materials. For those materials, the modified Campbell (SoilVision®, 2004) method was used to provide an estimate of this curve that was less prone to numerical instabilities. Table I-3-3 summarizes the soil types used in the numerical models, the method used to fit the SWCCs to the soils, and the method used to estimate the unsaturated hydraulic conductivity curves. Attachment B includes plots of the unsaturated hydraulic conductivity curves used in the numerical models.

3.4 Boundary Conditions

In the one-dimensional column models, boundary conditions were assigned to the upper and lower surfaces of the models, and the lateral boundaries were designated as no-flow boundaries. Each of the models is assigned an upper boundary condition that represents and simulates atmospheric conditions, and a lower boundary represented by a gradient boundary or the water table. The simulation of the LEP 'wet' area utilized two sets of upper boundary conditions: 1) a constant head boundary condition for the upper boundary to simulate the approximate 6-month period of ponded conditions (i.e., the constant head boundary supplied as much water to the model as necessary to maintain the ponded condition); and 2) a six- month period to simulate the portion of the year when the ground surface is exposed to atmospheric conditions. Because SVFlux™ does not provide a means of changing the boundary condition type during a simulation, a series of model runs were made using alternating constant head and atmospheric upper surface boundary conditions.

Because of the relatively greater depth to groundwater beneath FEP 1-4 (up to 65 feet bgs), the FEP 1-4 model used a gradient boundary for the lower boundary condition. This was done to eliminate unrealistic potential of the model to wick excessive water from the water table at a 65-foot depth. With a gradient boundary, the gradient, *i,* is fixed at the model boundary, and the model then calculates the flux at the boundary according to $q=ki$, where q is the flux rate and k is the unsaturated hydraulic conductivity. A gradient of 0.6 was determined to be an appropriate value based on likely actual gradients, model calibration results and because a larger gradient (i.e., a unit gradient equal to 1.0) was drying out the models in an unrealistic fashion. The models for the LEP ('wet' and 'dry' areas), UEP and FEP 5 used the water table for the lower boundary (about 45 feet for FEP 5, and about 20 feet for the LEP and UEP). At these relatively shallow depths, the water table would be expected to have a greater influence on soil water flux.

An osmotic suction parameter was included in the upper boundary condition applied to these models to simulate a salt crusting effect that reduces the evaporative flux. The osmotic suction parameter works by increasing the total soil suction at the surface of the model. Soil suction is a function of soil moisture, and becomes increasingly negative as the soil dries. The increased soil suction resulting from the inclusion of the osmotic suction parameter reduces the vapor pressure at the soil surface and concurrently reduces the vapor pressure gradient between the soil surface and the atmosphere. Because actual evaporation is a function of this vapor pressure gradient, the effect is to reduce the actual evaporation (Wilson, et al., 1997). In the Pond column models, the osmotic suction parameter was added to the simulated soil suction pressure. The osmotic suction was initially set at 70,000 kilopascals (KPa) for all of the models, which is an average value for osmotic suction when the crust mineralogy is unknown (M. Fredlund, pers. comm., 2009). However, for the FEP 5 model, the osmotic suction was raised to 140,000 KPa during calibration to bring simulated saturation of the model domain into reasonable agreement with the observed saturation (see Section 4.4).

3.5 Initial Conditions

Initial moisture conditions for the models were developed using SVFlux™ to establish a linear distribution of pressure head between the water table and the upper model boundary. Initial moisture conditions were at or near equilibrium (i.e., quasi steady-state condition) with boundary conditions at the start of the simulation for the LEP ‘dry’ model and for FEP 5, and required approximately 1,800 days for the UEP and approximately 1,500 days for FEP 1-4.

Equilibrium was indicated by a cessation of any long-term drying or wetting trends exhibited by the models. Initial conditions of the LEP ‘wet’ areas model were at or near-saturation, which was established by the simulation of a constant (five centimeter) head at the upper model boundary for a period of approximately five years. An example of a time-saturation plot that demonstrates the equilibration of initial conditions is presented in Figure I-3-1, which shows the percentage of saturation at four depths within one of the column models over the 15-year simulation period. The early part of the simulation (i.e., 0 to approximately 1,800 days) is marked by a persistent drying trend that indicates the model is still equilibrating with boundary conditions during this period. Following this initial equilibration period, the saturation within the model is characterized by short-term, seasonal variations that are superimposed on a quasi steady-state saturation condition.

3.6 Conceptual Models

The column models used for the simulations are based on conceptual models of the Pond sediments and underlying alluvial soils, atmospheric processes that interact with the unsaturated materials, subsurface moisture conditions observed in October 2008, and the depth of the water table beneath the Ponds. With the exception of the LEP ‘wet’ area model (described in Section 3.6.2), the atmospheric input parameters (i.e., precipitation and evaporation) are the same for all models (see Section 3.2). Because the model columns represent generalized conditions for each Pond, as depicted in Figure I-2-2, small-scale variations in soil types (vertical profiles intercepted by individual boreholes and observed variations in soil types in multiple boreholes in the same Pond) were not included in the column models because they are not representative of the facilities at a larger scale.

3.6.1 LEP 'Dry' Area Conceptual Model

A composite soil column is presented in Figure I-2-2 that represents the pond sediments and soils between the ground surface and the water table in the LEP 'dry' area. Figure I-3-2 presents a column of material types that were used to represent the soils in the composite soil columns. The physical and hydraulic properties of these materials are summarized in Table I-3-3. The mineral crust and evaporite crystals presented in the composited soil profile (Figure I-2-2) are not included as a material type for the LEP 'dry' area model column, but the effects of the crust (i.e., to reduce the evaporative flux from the model) is simulated by including an osmotic suction parameter in the numerical model that reduces evaporation when the soil surface becomes very dry (see Section 3.4). Observations of the asphalt liner indicate locally degraded areas, and the liner likely does not act as a continuous low hydraulic conductivity layer. Because of the uncertainties regarding the integrity of the asphalt liner, it was not included in the LEP 'dry' area column model.

Laboratory analyses of soils sampled from three LEP boreholes (Figure I-2-1) indicate that soil moisture conditions were near, or at, saturation in the samples, which is consistent with the borehole locations near or adjacent to the 'wet' areas. The three shallow soil samples were collected at an average depth of approximately 8.7 feet below ground surface (bgs) and were measured at 116, 115 and 97 percent saturation. The three deep soil samples collected at an average depth of approximately 17.8 feet were measured at 96, 81 and 98 percent saturation (Table I-2-1). The depth to the water table beneath the LEP is approximately 19 feet bgs.

As noted above, the boreholes used to characterize the LEP 'dry' area are located near the ponded areas (Figure I-2-1), and likely do not truly represent the 'dry' areas. Other areas of the LEP that are more distal from the areas of seasonal ponded water would likely exhibit lower saturation values that are more similar to those observed for the UEP, and likely change gradationally to more closely resemble the soils underlying the UEP and FEPs as the southern and western boundaries of the LEP are approached. However, because data are not available from the transitional areas, boreholes proximal to the 'wet' areas' were used for the LEP 'dry' area numerical model simulation.

3.6.2 LEP ‘Wet’ Area Conceptual Model

The composite soil column described above for the LEP ‘dry’ area conceptual model was also used for LEP ‘wet’ area model, as were the material types presented in Figure I-3-2 The difference between these two models is the application of the upper surface boundary condition. As stated previously, because SVFlux™ does not provide a means of changing the boundary condition type during a simulation, the LEP ‘wet’ area model required an alternating constant head and climate upper surface boundary condition to represent the seasonal condition of ponded water during the winter/early spring months and the summer/fall period when the standing meteoric water has evaporated.

To provide initial moisture contents for the set of alternating boundary conditions simulations for the LEP ‘wet’ area, a five-year simulation was first run using a constant head equal to five centimeters (cm). This initial constant head simulation saturated the underlying materials in the model, and these saturated conditions were used as initial conditions for the predictive simulations. The set of alternating boundary conditions simulations was then initiated using the final moisture conditions of the five-year simulation as the starting moisture conditions for a six-month simulation utilizing a climate boundary condition. A six-month constant-head simulation was subsequently run using the final moisture conditions of the first six-month climate boundary conditions simulation as the starting moisture conditions. This set of linked alternating boundary conditions simulations was continued for a total simulation time of five years. The climate boundary used for these simulations included the months of May through October, 2000, which was used to represent average conditions

3.6.3 UEP Conceptual Model

The composite soil column presented in Figure I-2-2 includes the pond sediments and two soil types between the ground surface and the water table. The material properties included in the UEP numerical model are shown on Figure I-3-2, and hydraulic properties of those materials are included in Table I-3-3.

Laboratory analyses of soils collected in three DPT boreholes beneath the UEP indicate that subsurface moisture conditions vary considerably from borehole site to borehole site across the facility (Table I-2-1). The median saturation percentage values from borehole OU4-UEP-07 (Figure I-2-1) was chosen to represent the UEP (measured saturation percentages of the shallow soils were 10, 48, and 104 percent, and measured saturation percentages of the deep soils were 56, 90 and 115 percent, respectively). The water table is located at approximately 21 feet bgs

3.6.4 FEP 5 Conceptual Model

A composited soil column is presented in Figure I-2-2 that represents the pond sediments and soils between the ground surface and the water table in FEP-5. Material types incorporated into the numerical model of FEP 5 are presented in Figure I-3-2, and the physical and hydraulic properties of those materials are included in Table I-3-3.

Laboratory analyses of soils collected in one DPT borehole beneath FEP 5 indicate that subsurface conditions are moderately dry at shallow depths, and at or near saturation in the deeper portion. Saturation percentages were measured at 67 and 110 percent for the shallow and deep zones, respectively. The water table is located at approximately 45 feet bgs.

3.6.5 FEP 1-4 Conceptual Model

The FEPs 1-4 area do not exhibit ponding, although an asphalt liner is present similar to that found in the LEP. A composited soil column is presented in Figure I-2-2 that represents the pond sediments and soils between the ground surface and the water table in the FEP. Material types incorporated into the numerical model of the LEP are presented in Figure I-3-2, and the physical and hydraulic properties of those materials are included in Table I-3-3. As described for the LEP conceptual model, the asphalt liner is not included in the column model.

Laboratory analyses of soils collected in one DPT borehole beneath the FEP 1-4 facilities indicate that subsurface materials are coarser-grained and conditions are drier in these facilities than in the LEP, with a shallow saturation percentage measured at 70 percent, and the deep moisture content measured at 67 percent of saturation. The water table beneath the FEP 1-4 facility is located at approximately 65 feet bgs.

SECTION 4.0
SIMULATION RESULTS

Comparisons of observed versus simulated saturation percentages for each of the Ponds indicate the appropriateness of the numerical models for predictive simulations (i.e., approximating the observed moisture conditions with the models). Table I-4-1 presents the results of moisture content analyses from the borehole samples and the range of moisture contents simulated by the models at depths similar to the sample depths over the 15-year simulation period. Descriptions of simulation results for each model are provided below. Although borehole sample moisture content results that are greater than 100 percent should be considered to be at 100 percent saturation (see Section 2.2), the actual laboratory results are presented in Table I-4-1 to convey the information that these results imply (i.e., that the samples contain some percentage of swelling clay).

Table I-4-2 provides a summary of simulation results on an annual average basis, including precipitation, evaporation, net flux at the upper model boundary (i.e., flux into or out of the model domain), and the flux of water at the deep flux line location shown on Figure I-3-2 for each model column. As described in Section 3.5, the UEP and FEP 1-4 models equilibrated after approximately 1,800 simulation days and 1,500 simulation days, respectively (as described below, both models were substantially equilibrated after approximately three years). Volumes and fluxes reported in Table I-4-2 represent simulation years four through 15, so that all results are based on the same simulation years. Simulation results for each of the models on a yearly basis are provided in Tables I-4-3 through I-4-7.

Three flux lines were designated in each of the models (Figure I-3-2) to evaluate the movement of soil water at various depths (flux lines are a tool included in SVFlux™ that allows the user to monitor and record the flux of soil water anywhere in the column model). Flux lines in the two LEP models were in the VLT, the middle of silty sand with clay, and in the middle of the silty sand unit. The UEP model included flux lines in Pond sediments, the middle of silty sand with clay, and the middle of the silty sand unit. The FEP-5 model included flux lines in Pond sediments, near the top of the silty sand with gravel, and near the bottom of the silty sand with gravel. Flux lines in the FEP 1-4 model were included near the top of the silty sand with gravel, near the middle of the silty sand with gravel, and near the bottom of the silty sand with gravel. The deepest flux line in each column model was used to estimate deep soil water movement (i.e., whether soil moisture moved up or down, the flux rate, and the total cumulative flux volume).

A tool for monitoring saturation at various locations within the model domain, called point saturation monitors (saturation points), is also provided by SVFlux™. The saturation points provide a history of the degree of saturation at designated locations within the column models for the simulation period, and are used for comparing observed saturation percentage with simulated saturation percentage. Each of the column models includes several of these point saturation monitors, as shown on Figure I-3-2. Although observed and simulated saturation percentages may differ, the comparisons described below between the observed and simulated saturation percentages indicated reasonable agreement considering: 1) the single-point-in-time nature of observed conditions in a dynamic vadose zone environment; and 2) the small-scale heterogeneity in the borehole samples, which cannot be incorporated into the generalized column models. The following terms are used in the simulation results summarized below:

- ‘Potential evaporative flux’ is the amount of evaporation that would occur if soil water were not a limiting factor;
- ‘Actual evaporative flux’ is the amount of soil water removed from the column model through evaporation (if soil water were always fully available in the model, actual evaporation would approach the potential evaporation);
- ‘Cumulative annual flux’ is the total net flux for a single simulation year;
- ‘Average annual flux’ is the average of the cumulative annual fluxes; and
- ‘Total cumulative flux’ is the sum of cumulative annual fluxes for the simulation period (i.e., the ‘total net flux’).

The relationship between saturation percentage and flux rates in the column models is an important concept in reviewing the simulation results described below. As the saturation percentage increases, the hydraulic conductivity (i.e., flux rate) increases according to the unsaturated hydraulic conductivity curve, which relates soil moisture to hydraulic conductivity. The end point is 100 percent saturation and the associated saturated hydraulic conductivity value.

4.1 LEP ‘Dry’ Area Simulation Results

The LEP ‘dry’ area simulation produced a reasonable agreement between the observed and simulated saturation for shallow and deep levels (Table I-4-1). Observed saturation percentages ranged from 97 to 116 percent at shallow depths (approximately 2.7 meters bgs), and from 81 to 98 percent at deeper levels (approximately 4.9 to 5.8 meters bgs). The model-simulated saturation ranges between approximately 85 and 90 percent saturation at the comparable shallow depth, and approximately 90 to 95 percent at the comparable deep level.

Figure I-4-1 shows the saturation history for the simulation at five depths in the model domain, as monitored by the saturation points described above. Figure I-4-1 also shows that the near-surface (approximately 0.2 meters bgs) of the model varied between about 75 and 100 percent saturation, and that the deepest portion of the model (approximately 5.6 meters bgs) remained at a fairly constant value of approximately 90 percent. The VLT saturation monitoring point (approximately 0.46 meters bgs) remained at approximately 20 percent dry throughout the simulation, but spiked to about 65 percent in response to short-term precipitation events. The deeper portions of the column model displayed a fairly constant saturation with time (i.e., the simulation remained in approximate equilibrium with model boundary conditions (Figure I-4-1)).

Years four through 15 of the simulation period (Table I-4-2) indicated: 1) an average net downward flux of water of approximately 0.0012 meters per year (m/yr) measured at the deep flux line; and 2) a cumulative annual deep flux range between an upward flux of 0.0087 m/yr and a downward flux of 0.0137 m/yr (Table I-4-3). Five of the simulation years for this model showed a downward net annual flux, and the remaining 10 simulation years indicated an upward net annual flux. Cumulative annual fluxes at the three flux lines included in the model are presented in Figures I-4-2 through I-4-4.

The total cumulative (i.e., net) flux at the deepest flux line (approximately 4.2 meters bgs) in the model was approximately 0.013 meters downward after 15 years of simulation (Figure I-4-2). Figure I-4-2 also shows that the flux of water may be either upward or downward depending on longer-term precipitation and evaporation cycles. For example, after approximately 3,800 days of simulation time, the cumulative total flux was approximately 0.025 meters upward. Smaller-scale fluctuations shown on Figure I-4-2 reflect seasonal changes in flux direction in response to winter/spring precipitation events (i.e., downward flux) and drier, evaporation-dominated summer periods (i.e., upward flux).

Plots for the two upper flux lines (Figures I-4-3 and I-4-4) exhibited a similar trend at the deep flux line (Figure I-4-2) with greater seasonal fluctuations due to their relative proximity to the upper model boundary. These plots indicate that greater volumes of water moved both upward and downward in the upper portions of the column model domain during the simulation than in the deeper portion.

Figure I-4-5 illustrates the simulated cumulative climate boundary fluxes including the potential evaporative flux, (modeled) actual evaporative flux, precipitation, and net flux at the upper boundary of the model. The net atmospheric boundary flux is upward, out of the model (negative flux), for the first 3,800 days of the simulation period, and into the column model (positive flux) for the remainder of the simulation, a similar trend to that observed at the deep flux line (Figure I-4-2). Figure I-4-6 provides a detailed plot (i.e., larger vertical scale) of the net flux line for this simulation to better illustrate the behavior of soil moisture in the upper portion of the model.

4.2 LEP 'Wet' Area Simulation Results

Moisture conditions were at or near saturation throughout the LEP 'wet' area column model for the beginning of the simulation period (Figure I-4-7), resulting from the five-year constant head simulation used for initial moisture conditions in the five-year linked climate boundary/constant head boundary simulations (see Section 3.6.2). Saturation profiles were selected to illustrate the moisture conditions in this model, rather than the saturation history plots, because they provide more information about the simulated moisture profile for the short-duration, linked simulations.

As shown in Figure I-4-7, initial saturation percentages in the column model varied between 94 and 100 percent, with the majority of the alluvial soils at 94 percent. The saturation percentage plot at 4.5 years into the simulation (Figure I-4-8) shows the saturation percentage for the Pond sediments (approximately 0.0 to 2.0 meters bgs) in the 70 to 80 percent range and the VLT (approximately 0.2 to 0.6 meters bgs) saturation percentage at approximately 20 percent, resulting from the effects of the last climate boundary segment of the linked six-month simulations. Figure I-4-9 shows the modeled saturation profile at five years into the simulation period, which indicates the rapid return of (near) saturated conditions in the upper (Pond sediment and VLT sub-liner) portion of the column model, and an alluvial soil profile that is similar to the initial condition (Figure I-4-7).

For the 5-year linked simulation period, the LEP 'wet' area model indicated a downward net flux of water, as indicated by the cumulative flux plots presented in Figures I-4-10 through I-4-12 (deep, intermediate and shallow levels, respectively). These cumulative flux plots demonstrate the decreasing effect of the upper atmospheric boundary condition on the downward flux at deeper levels of the column model. Table I-4-4 presents the cumulative deep flux for each of the 10 six-month simulation periods. Results for the first six-month simulation period, which immediately followed the five-year constant head initial period and utilized an atmospheric boundary, indicated a cumulative downward flux at the deep flux line of approximately 0.0310 meters The remainder of the six-month cumulative flux values ranged from 0.0130 meters downward to 0.0157 meters downward.

The greater magnitude of the initial six-month simulation period cumulative deep flux is attributed to drain-down of the column model following the initial five-year constant head simulation period. The cumulative flux at the deepest flux line in the model (approximately 4.2 meters bgs) indicates that the flux at this level in the model domain is consistently downward (Figure I-4-10). Plots of cumulative fluxes at the depths of the intermediate and shallow flux lines (Figures I-4-11 and I-4-12, respectively) show seasonal fluctuations with periods of upward flux as the upper boundary changed to an atmospheric boundary condition (i.e., the effect of evaporation), which resulted in localized reduction of saturated percentages within the column model. However, as these figures illustrate, the long-term net flux for the LEP 'wet' area model is downward.

4.3 UEP Simulation Results

Simulation of the UEP produced a reasonable agreement between the observed and simulated saturation for shallow and deep levels in borehole OU4-UEP-07 (Figure I-2-1; as described in Section 3.6.5, saturation percentage values in borehole OU4-UEP-07 represented the median values from the alluvial soils underlying the UEP). Observed saturation percentages at OU4-UEP-07 were 48 percent at approximately 2.6 meters bgs, and about 90 percent at approximately 6.0 meters bgs (Table I-4-1). For comparable depths, model-simulated saturation values ranged between 50 and 60 percent and between 65 to 75 percent. Figure I-4-13 shows the saturation history for the simulation at four depths in the column model, monitored by the saturation points shown in Figure I-3-2. Figure I-4-13 indicates that the UEP model required approximately 1,800 days of simulation time to equilibrate with the model boundary conditions, indicated by the overall drying trend at the saturation points (as previously stated, the model was substantially in equilibrium after three years).

Years four through 15 of the simulation period indicated an average net upward flux of soil water of approximately 0.2633 m/yr (Table I-4-2), measured at the deep flux line. The cumulative annual deep flux for years four through 15 of the simulation period remained upward for the entire period, and ranged between 0.1899 m/yr and 0.3114 m/yr (Table I-4-5). Cumulative fluxes at the three flux lines included in the model are presented in Figures I-4-14 through I-4-16 (deep, intermediate and shallow, respectively). The cumulative upward flux at the deepest flux line (approximate 4.8-meter depth) in the column model was approximately 1.78 meters after the 15-year simulation period (Figure I-4-14). Figure I-4-16 illustrates both the seasonal variation in soil water flux at the shallow flux line depth and the long-term upward trend. Figure I-4-17 indicates a consistent upward net flux for UEP Pond sediments and underlying soils throughout the 15-year simulation period.

4.4 FEP-5 Simulation Results

The FEP 5 (Thumb Pond) simulation produced reasonable agreement between the observed and simulated saturation values for shallow and deep levels in the column model. Observed saturation percentages in FEP 5 were 67 percent at approximately 2.7 meters bgs and 110 percent at approximately 13.4 meters bgs (Table I-4-1). The model-simulated saturation values ranged between approximately 60 and 65 percent saturation at 2.7 meters bgs, and approximately 100 percent at 13.4 meters bgs. Figure I-4-18 shows the saturation history for the simulation at four depths in the column model, indicating that this model was close to equilibrium from the start of the simulation. Figure I-4-18 shows that: 1) the near-surface (approximately 0.24 meters bgs) of the model varied between about 10 and 100 percent saturation; 2) the base of the Pond sediments (approximately 1.2 meters bgs) varied between about 65 and 95 percent saturation; and 3) the deeper portion of the model (approximately 10.1 meters bgs) remaining at a fairly constant approximately 78 percent. The water table corresponds to the deepest monitoring point and observed (sampled) depth (13.4 meters bgs), and remained at saturation throughout the simulation (this saturation plot is not included on Figure I-4-18).

Years four through 15 of the simulation indicated: 1) an average net upward flux of soil water of approximately 0.1871 m/yr (Table I-4-2), measured at the deep flux line; and 2) a cumulative annual deep flux that ranged between an upward flux of 0.0764 m/yr and an upward flux of 0.2564 m/yr (Table I-4-6). Cumulative fluxes at the three flux lines included in the model are presented in Figures I-4-19 through I-4-21 (deep, intermediate and shallow, respectively). The total cumulative flux at the deepest flux line (approximately 11.7 meters bgs) in the model was approximately 2.2 meters upward after the 15-year simulation period (Figure I-4-19). Seasonal variations in the movement of water are evident in the plot of the shallow flux line (Figure I-4-21). Figure I-4-22 shows that the net flux for this simulation remains upward for the entire simulation period.

4.5 FEP 1-4 Simulation Results

Reasonable agreement between the observed and simulated saturation values for the shallow and deep levels of the FEP 1-4 column model was achieved. The observed saturation percentage was

70 percent at approximately 1.3 meters bgs, and 67 percent at approximately 15.9 meters bgs (see Table I-4-1). The model-simulated saturation values ranged between 50 and 70 percent saturation at 1.3 meters bgs, and 60 and 65 percent at 15.9 meters bgs following an initial drying at the deeper level (Figure I-4-23) over the first 1,500 days of the simulation. As previously stated, the model was substantially at equilibrium after approximately three years of simulation. Figure I-4-23 shows the near-surface (approximately 0.15 meters bgs) of the model varying between about 70 and 100 percent saturation, and the deepest portion of the model (approximately 15.9 meters bgs) declining slightly for the first approximately 1,500 days and then reaching a fairly constant approximately 60 percent.

For years four through 15 of the simulation, the model indicates an average net downward flux of water of approximately 0.0026 m/yr (Table I-4-2), measured at the deep flux line. Over years four through 15 of the simulation, the cumulative annual deep flux ranges between a downward flux of 0.0024 m/yr and a downward flux of 0.0034 m/yr (Table I-4-7). Cumulative annual fluxes at the three flux lines included in the model are presented in Figures I-4-24 through I-4-26. The total cumulative flux at the deepest flux line (approximately 11.6 meters bgs) in the model is approximately 0.043 meters downward after 15 years of simulation (Figure I-4-24).

Cumulative flux plots for the intermediate and shallow flux lines (Figures I-4-25 and I-4-26) show the same overall trend as the deep flux line (Figure I-4-24). The intermediate cumulative flux (Figure I-4-25) shows some initial equalization with the boundary conditions over the first approximate 1,500 days. Shallow flux (Figure I-4-26) reflects seasonal trends of evaporation and precipitation, with an overall trend of downward flux. Figure I-4-27 shows that the net flux is towards the water table for the simulation period (i.e., a positive value into the column model).

4.6 Discussion of Simulation Results

Based on the model simulation results summarized in the previous sections, two of the Ponds (LEP and FEP 1-4), demonstrated the potential to flux meteoric water through the vadose zone to groundwater. The estimated flux rates derived for these simulations, when integrated over the acreage values for these Ponds, result in the following annual estimated volumes of water that could potentially migrate to groundwater beneath these Ponds:

- Approximately 0.31 acre-feet per year (ac ft/yr) for the LEP 'dry' areas, based on an estimated flux rate of 0.0012 m/yr and an area of 79.5 acres, equivalent to 0.19 gpm;
- Approximately 1.13 ac ft/yr for the LEP 'wet' areas, based on an estimate flux rate of 0.016 m/yr and an area of 21.5 acres, equivalent to 0.70 gpm; and
- Approximately 0.15 ac ft/yr for FEP 1-4, based on an estimated flux rate of 0.0026 m/yr and an area of 17.8 acres, equivalent to 0.09 gpm.

As discussed in Section 3.6.1, hydraulic property values for soils underlying the LEP were collected from boreholes proximal to 'wet' (intermittently ponded) areas, and that there is likely a gradation in subsurface properties towards the UEP and/or FEP 5 that would result in smaller downward deep flux rates, or possibly upward net flux rates, from these 'dry' LEP areas. Because the upper boundary climate condition input was the same for all models, it can be concluded that the different vadose zone simulation results described above in term of flux rates and net soil water movement direction in the subsurface are strongly dependent on the physical and hydraulic characteristics of the Pond sediments and underlying alluvial soils. For example, the deeper soils underlying the LEP and the UEP were observed to be similar (i.e., silty sand with clay and silty sand) as was the depth to groundwater, but the simulation results presented above indicated a net annual average downward flux for the LEP 'wet' area model and a net annual average upward flux for the UEP column model. This difference can be explained by: 1) Pond sediment thickness (i.e., the thicker sequence of very fine grained Pond sediments observed in the UEP can more readily retain and evaporate soils moisture); 2) Pond sediment characteristics (i.e., crystal formation in the LEP and associated osmotic suction differences); 3) the presence of the LEP liner (its precise role is uncertain, resulting in its exclusion from the LEP 'wet' area column model); and 4) the topographically depressed center portion of the LEP that, along with Pond sediment characteristics, serve to seasonally pond meteoric water and maintain (near) saturated conditions in the subsurface.

The effect on simulation results of varying some model input parameters (i.e., the application of storm intensity or pan factor) was tested in the sensitivity simulations described in Section 5.0. Given the limited available data for Pond sediment and soil hydraulic properties, the physical properties of these materials were not subjected to sensitivity analyses.

SECTION 5.0
MODEL SENSITIVITY

The 'base-case' results presented in Section 4.0 were designed to simulate observed material hydraulic properties under the physical (i.e., climate) conditions expected for the Site. In general, numerical models are subject to an interpretation of data that is not always complete or fully understood. Therefore, sensitivity analyses were conducted to test the sensitivity of the models to changes in model input parameters and assumptions. The column models selected for sensitivity analyses were the: 1) UEP, to validate or refute the conclusion that, under all anticipated climate conditions, the UEP is a net evaporative soil moisture system; and 2) the LEP 'dry' areas because less confidence should be placed in the results for this column model due to the use of LEP 'wet area soil hydraulic properties and, as described in Section 4.1, because of the somewhat ambiguous results for this column model:

- An average net downward flux of water of approximately 0.0012 meters per year (m/yr) measured at the deep flux line;
- A cumulative annual deep flux range between an upward flux of 0.0002 m/yr and a downward flux of 0.0137 m/yr; and
- Five of the simulation years for this model showed a downward net annual flux, and the remaining 10 simulation years indicated an upward net annual flux.

Model input parameters that were varied in the sensitivity runs included: 1) the osmotic suction magnitude; 2) the storm intensity (i.e., the time over which each storm event is distributed); 3) the pan factor applied to the pan evaporation data (Section 3.2); and 4) the use of a gradient boundary versus a water table boundary for the lower model boundary condition. A total of 14 sensitivity simulations were run. For each model, the osmotic suction, storm intensity, and pan factor variable were input at one higher and one lower value than the values used in the predictive simulations presented above. For the gradient versus water table lower boundary condition sensitivity analysis, each model was simulated with a gradient boundary for the lower boundary condition, and these results were compared with the results of the base-case predictive simulations, which used water table boundary conditions.

Table I-5-1 presents the input parameters that were varied, the nature or magnitude of the parameter variations, and the resulting changes in average annual deep flux. As presented in Section 4.0, flux values from the first three years of the simulations are not included in the averaged flux results so that all simulations are compared on an equal basis. Results for each of the sensitivity runs reported on a yearly basis are presented in Tables I-5-2 through I-5-15.

5.1 Osmotic Suction Sensitivity Results

The osmotic suction was set at 70,000 KPa for all 'base-case' simulation results. Sensitivity runs were conducted to test the sensitivity of the LEP 'dry' area and UEP column model results to the osmotic suction parameter set at 30,000 and 120,000 KPa. A reduction in the osmotic suction parameter tends to increase the evaporative flux (i.e., more potential for upward flux to the atmosphere from the column model), and an increase in the osmotic suction parameter tends to decrease the evaporative flux (i.e., more potential for downward flux from the column model).

For the LEP 'dry' areas model, reducing the osmotic suction input parameter to 30,000 KPa changed the net flux from an average annual downward flux to an average upward flux of 0.0200 m/yr (Table I-5-1). None of the simulation years showed a downward flux to the water table, and annual cumulative upward fluxes for simulation years four through 15 ranged from 0.0057 meters to 0.0331 meters (Table I-5-2).

Increasing the osmotic suction parameter to 120,000 KPa in the LEP model caused some numerical instabilities in the model related to domain saturation, and this model would not run for more than 10 years of simulation time. Therefore, the results presented herein are for 10 years of simulation time. The higher osmotic suction input parameter value resulted in an increase in the annual average downward flux from 0.0012 m/yr in the 'base-case' simulation to 0.004 m/yr (Table I-5-1). A downward flux was indicated for nine of the 10 completed simulation years, with the magnitude of the annual cumulative flux for simulation years four through 10 ranging from an upward flux of 0.0003 meters to a downward flux of 0.0115 meters (Table I-5-3).

Reducing the osmotic suction parameter to 30,000 KPa for the UEP model, increased the average annual upward flux from 0.263 m/yr to 0.434 m/yr (Table I-5-1). All of the simulation years results indicate a cumulative annual upward flux, which ranges from 0.3388 meters to 0.4851 meters (Table I-5-4) for simulation years four through 15. Increasing the osmotic suction parameter to 120,000 KPa in the UEP model decreased the annual average upward flux from 0.263 m/yr in the base-case simulation to 0.063 m/yr. All of the simulation years results indicate a cumulative annual upward flux, which ranges from 0.029 meters to 0.100 meters (Table I-5-5) for simulation years four through 15.

5.2 Storm Intensity Sensitivity Results

The storm intensity (i.e., the duration of precipitation for any day in which precipitation occurs) was set for an eight-hour period for the base-case simulation results presented in Section 4.0. Modifying the storm intensity changes the rate of application of precipitation to the upper surface of the column model, thereby creating the possibility of increasing or decreasing the net flux into or out of the model domain. Sensitivity runs were conducted to test the sensitivity of the LEP 'dry' areas and UEP results with the storm intensity period at four and 12 hours. A parabolic storm shape was used in all of the models (see Section 3.2).

A decrease in the storm intensity value in the LEP column model, from eight to four hours, resulted in a small reduction in the downward average annual flux from 0.0017 to 0.0015 m/yr (Table I-5-1). Cumulative annual fluxes were downward for five out of the 15 simulation years, with the annual values ranging from 0.0084 meters upward to 0.014 meters downward (Table I-5-6). Increasing the storm intensity in the LEP model from eight to 12 hours resulted in a small increase in the downward average annual flux from 0.0017 to 0.0019 m/yr (Table I-5-1). Cumulative annual fluxes were downward for six of the 15 simulation years, with the annual values ranging from 0.0080 meters upward to 0.0145 meters downward (Table I-5-7).

For the UEP model, decreasing the storm intensity from an eight-hour to a four-hour period or increasing the storm intensity from an eight-hour to a 12-hour storm intensity did not change the average annual flux from the upward average annual flux of 0.263 m/yr result from the base-case model (Table I-5-1). Cumulative annual fluxes were upward for each year of the simulations (Tables I-5-8 and I-5-9). Storm intensity generally has little effect on models with a net upward flux (Fredlund, 2009).

5.3 Pan Factor Sensitivity Results

Pan evaporation data from the Lahontan COOP site (Section 3.2) were multiplied by a pan factor of 0.7 to produce potential evaporation input for use in the base-case simulations. As described in Section 3.2, evaporation data were adjusted by a pan coefficient of 0.7 to correct for factors (e.g., storage and transfer of heat to the water from the sides of the evaporation pan), which may increase the evaporation rate in an open pan with respect to the potential evaporation from bare soil (UNFAO, 1998). The effect of the pan coefficient is to lower the potential evaporative flux indicated by pan evaporation data (as the pan factor decreases, potential evaporation decreases). Sensitivity runs were done on the LEP and UEP models using pan factors of 0.55 and 0.35 to test the effect of reducing potential evaporation on the simulation results discussed in Section 4.0.

For the LEP model, the numerical models became saturated using either of the lower pan factors. It was therefore necessary to use the runoff parameter in SVFlux. The runoff parameter limits the maximum pore-water pressure to zero kPa, and any additional water that is applied is classified as runoff. The effect of adding the runoff parameter to the simulations was to change the small downward average flux to a small upward flux for both of the pan factor sensitivity simulations for the LEP 'dry' area model. As a result, no direct comparison of the LEP base-case simulation with the two sensitivity simulations presented herein can be made. However, the two sensitivity simulations using different pan factors can be compared:

- A pan factor of 0.35 for the LEP model resulted in a small average annual upward flux of 8.1 E-04 m/yr (Table I-5-1). Cumulative annual fluxes were upward for nine of the 15 simulation years, and varied from a downward flux of 0.0085 meters to an upward flux of 0.0088 meters (Table I-5-10).
- A pan factor of 0.55 for the LEP model resulted in a small average annual upward flux of 0.0036 m/yr (Table I-5-1). Cumulative annual fluxes were upward for 13 of the 15 simulation years, and varied from a downward flux of 0.0052 meters to an upward flux of 0.0112 meters (Table I-5-11).

Using a pan factor of 0.35 for the UEP model resulted in a small average annual upward flux of 0.080 m/yr compared with the UEP base-case average annual upward flux of 0.263 meters (Table I-5-1). For the 0.35 pan factor simulation, cumulative annual fluxes were upward for all 15 simulation years. For simulation years four through 15, the flux varied from 0.038 meters to 0.121 meters (Table I-5-12).

Using a pan factor of 0.55 for the UEP model resulted in an average annual upward flux of 0.198 m/yr, compared with the UEP base-case average annual upward flux of 0.263 meters (Table I-5-1). For simulation years four through 15, annual cumulative fluxes were upward for all simulation years, and varied from 0.141 meters to 0.249 meters (Table I-5-13).

5.4 Lower Boundary Condition Sensitivity Results

The lower boundaries for both the LEP and the UEP were set as head boundary (water table) conditions for the simulations results presented in Section 4.0. Two sensitivity runs were conducted to determine what changes to the results may be observed by changing the lower boundary conditions to gradient conditions for each of these models. As described in Section 3.4, the value of the gradient was set to 0.6 for each of these simulations.

For the LEP 'dry' areas model, changing the lower boundary to a gradient boundary condition caused an increase in the average annual flux from downward at 0.0017 m/yr in the base-case simulation to downward at 0.018 m/yr in the gradient boundary simulation (Table I-5-1). In the LEP base-case simulation, annual cumulative fluxes were downward for five of the 15 simulation years, with the flux values for simulation years four through 15 ranging from 0.008 meters upward to 0.014 meters downward (Table I-4-3). In the LEP gradient lower boundary simulation, annual cumulative fluxes were downward in all 15 simulation years, and flux values for simulation years four through 15 ranged from 0.005 meters to 0.030 meters (Table I-5-14).

For the UEP model, changing the lower boundary to a gradient boundary condition caused a decrease in the average annual upward flux from 0.263 m/yr to 0.0083 m/yr (Table I-5-1). In the UEP base-case simulation, annual cumulative fluxes were upward in all 15 simulation years, and flux values for simulation years four through 15 ranged from 0.190 meters upward to 0.311 meters upward (Table I-4-5). In the UEP gradient lower boundary simulation, annual cumulative fluxes for simulation years four through 15 were upward for five of the 15 simulation years, and the flux values ranged from 0.0244 meters downward to 0.0547 meters upward (Table I-5-15).

5.5 Discussion of Sensitivity Simulation Results

Sensitivity simulations indicate that the column models discussed above are:

- Relatively sensitive to changes in model input parameters that influence the evaporative flux (i.e., the osmotic suction parameter and the potential evaporation);
- Very sensitive to the type of lower boundary condition; and
- Relatively insensitive to the storm intensity distribution, particularly if the model indicates a net upward flux.

Increasing the evaporative flux over the values used in the base-case simulation by reducing the osmotic suction parameter had the effect of increasing the simulated upward average annual flux in the UEP by a factor of about two. By reducing the evaporative flux through an increase in the osmotic suction parameter, the simulated downward average annual flux in the LEP ‘dry’ areas increased by a factor of about three and the simulated upward average annual flux in the UEP was reduced by a factor of approximately four.

Decreasing the potential evaporative flux by applying a smaller pan factor to the pan evaporation data had similar effects to those resulting from changes in the osmotic suction parameter. A reduction in the applied pan factor from 0.7 to 0.55 reduced the upward average annual flux in the UEP model by a factor of approximately 1.4, and a reduction in the applied pan factor to 0.35 reduced the upward flux by a factor of approximately three. Although the results of the pan factor sensitivity simulation can not be compared directly with the base-case simulation for the LEP model because of the inclusion of the runoff factor in the sensitivity simulations, the reduction in the pan factor in the sensitivity simulations from 0.55 to 0.35 reduced the average annual upward flux by a factor of about four.

The incorporation of a gradient boundary for the lower model boundary condition increased the downward annual average flux in the LEP 'wet' areas model by a factor of about 10, and decreased the upward annual average flux in the UEP model by a factor of about 30. An increase in the downward fluxes in both models was anticipated with this change in boundary conditions because the gradient boundary condition forces a gradient in the model, thereby inducing the downward movement of soil water during times when the presence of a head boundary that simulates a water table may not have the same gradient (i.e., during times of high evaporative flux). The head boundary condition incorporated in the base-case simulations for these models is considered to be a better representation of the subsurface conditions for both of these models because the lower model boundaries are at positions coincident with the physical location of the water table, from which water would tend to wick upward rather than having a condition of a downward pressure gradient However, the results of the gradient boundary sensitivity simulations suggest that the results presented for the FEP 1-4 model (Section 4.5) may indicate a potential for greater downward flux than would be predicted by the incorporation of a head boundary in that model.

SECTION 6.0
REFERENCES CITED

Brown and Caldwell, 2008a, *Anaconda Evaporation Ponds Removal Action Characterization Work Plan*, Prepared for Atlantic Richfield Company, September 15.

Brown and Caldwell, 2008b, *Air Quality Monitoring Program Data Summary Report*. Prepared for Atlantic Richfield Company, May 29.

Brown and Caldwell, 2009, *Anaconda Evaporation Pond Removal Action Characterization Data Summary Report*, Prepared for Atlantic Richfield Company, June 12.,

Brown and Caldwell and Integral Consulting Inc., 2009, *Conceptual Site Model, Revision 3,* Prepared for the Atlantic Richfield Company. January 30.

Domenico, Patrick A., and Schwartz, Franklin W., 1990, "Physical and Chemical Hydrogeology", John Wiley & Sons, Inc.

EPA Region 9, 2007, Administrative Order for the Remedial Investigation and Feasibility Study in the Matter of Anaconda/Yerington Mine Site, Yerington, Lyon County, Nevada: Atlantic Richfield, Respondent, U.S. EPA Region 9, Docket No. 9-2007-0005. Proceeding under Section 106(a) of CERCLA, as amended, 42 USC § 9606(a) including Attachment A: Scope of Work for the Remedial Investigations/Feasibility Studies Continued Response Action, January 12.

Fredlund, D.G., Xing, A., and Huang, S., 1994, "Predicting the permeability function for unsaturated soil using the soil-water characteristic curve", Canadian Geotechnical Journal, Vol. 31, No. 3, pp. 533-546.

Fredlund, M.D., Fredlund, D.G., and Wilson, G.W., 1997, "Prediction of the Soil-Water Characteristic Curve from Grain-Size Distribution and Volume-Mass Properties", 3rd Brazilian Symposium on Unsaturated Soils, Rio de Janeiro, April 22-25.

Fredlund, M.D., 2009, Personal communication, May 12.

Hillel, Daniel, 1980, "Fundamentals of Soil Physics", Academic Press, Inc., San Diego, California.

SoilVision, 2004, "SoilVision Users Manual", SoilVision® Systems LTD, Saskatoon, Saskatchewan, Canada.

SoilVision Systems, 2008, "SVFlux, 2D/3D Seepage Modeling Software", Version 7, SoilVision Systems Ltd., Saskatoon, Saskatchewan, Canada..

UNFAO, 1998, Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., "Crop evapo-transpiration; Guidelines for computing crop water requirements," FAO Irrigation and Drainage Paper No. 56, Rome, Italy.

Wilson, G.W., Fredlund, D.G., and Barbour, S.L., 1997, "The Effect Of Soil Suction On Evaporative Fluxes From Soil Surfaces", Can. Geotech. J. 34: 145-155 (1997).

WRCC, 2007, Yerington, Nevada (269229): Period NCDC 1971-2000 Monthly Normals. Western Regional Climate Center. http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv9229.